Palaeogeography, Palaeoclimatology, Palaeoecology 510 (2018) 26–30

Contents lists available at ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

journal homepage: www.elsevier.com/locate/palaeo

The Plio-Pleistocene 405-kyr climate cycles

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ARTICLE INFO

Article history:
Received 7 April 2017
Received in revised form 19 July 2017
Accepted 20 July 2017
Available online 23 July 2017

ABSTRACT

The 405-kyr cycles in proxy records for the East Asian summer monsoon and global ice volume intensified and became phase-locked to eccentricity forcing at ~4.5 Ma. We revised previous forcing mechanism hypothesis for Pliocene intensification of the 405-kyr cycles in paleoclimatic records and proposed that the establishment of salinity difference between the Pacific Ocean and the Caribbean Sea at ~4.5 Ma triggered an ocean-air positive feedback mechanism. This feedback mechanism caused simultaneous climate cooling and East Asian summer monsoon intensification and made the two different climate components have a clipped response to insolation forcing and, thus, intensified sensitivity to eccentricity variations. Weakening of the 405-kyr cycles in monsoon and ice volume records between 2 and 1 Ma (mid-Pleistocene transition) was likely to be attributed to frequency modulation that transfer power of the 405-kyr band to the 100-kyr band, which was triggered by changes in the oceanic carbon storage of the Southern Ocean.

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1. Introduction

Forcing mechanism for intensive onset of the Northern Hemisphere glaciations (NHG) at ~2.75 Ma (An et al., 1999; Cane and Molnar, 2001; Haug et al., 2005; Lunt et al., 2008a; Nie et al., 2014; Raymo, 1994; Shackleton and Al, 1984) is one outstanding question in paleoclimate research. Numerous hypotheses have been proposed for this event but no consensus has been reached after decades of studies. Here we aim to narrow down forcing mechanisms hypotheses for this event by considering the Plio-Pleistocene 405-kyr (also called 400-kyr or 413-kyr) climatic variability. The 405-kyr climate cycles are an important component of climate variations and are receiving more and more attention in recent years (Imbrie et al., 1993; Kashiwaya et al., 2003; Lisiecki and Raymo, 2007; Nie et al., 2008c; Paillard and Donnadieu, 2014; Pälike et al., 2006; Russon et al., 2010; Tian et al., 2014; Wang et al., 2004, 2010; Xiong et al., 2006). Considering the 405-kyr-band climatic cycles will have the potentials for providing additional bounds to narrow down forcing mechanisms for the NHG. Any forcing mechanism hypothesis for the NHG will need to be compatible with the 405-kyr-band variability during the Plio-Pleistocene period.

In order for ice sheets to grow and sustain, two requirements are needed: plenty moisture source and cooling climate (Haug et al., 2005). Although the intensive NHG did not start until ~2.75 Ma, it is clear that starting from ~4.5 Ma, NH ice volume had developed an increasing trend (Figs. 1 and 2), requiring that the forcing mechanism candidate for the NHG has to be able to supply not only decreased temperature but also increased moisture from 4.5 to 2.7 Ma. The first category model for the NHG is lowering atmospheric CO_2 concentration during the Pliocene (Lunt et al., 2008a). However, one weakness of this hypothesis is that decreased CO_2 concentration and temperature will suppress evaporation and, thus, moisture availability for ice sheets to grow. Thus, CO_2 forcing is important but can only play part of the role in forcing the NHG. The second category model is Pliocene uplift of the Tibetan Plateau, which can not only cause CO_2 level decrease, but also intensify summer monsoon circulation and provide moisture source for ice sheets to grow (An et al., 2001; Mudelsee and Raymo, 2005). However, evidence supporting intensive uplift of the Tibetan Plateau during the late Pliocene is controversial (An et al., 2001; Nie et al., 2008c; Zhang et al., 2001). The third category model for the NHG is closure of the Indonesian Seaway (Cane and Molnar, 2001), which likely caused ending of a permanent El Niño condition during the late Pliocene and caused climate cooling (Cane and Molnar, 2001; Fedorov et al., 2006). However, a recent atmosphere-ocean general circulation model simulation suggests that role of this event to the NHG was negligible (Haywood et al., 2007).

Another hypothesis for the onset of NHG is that the closure of the Isthmus of Panama intensified the Gulf Stream, which brought warmer water to the North Atlantic, enabling greater evaporation and snow precipitation that built northern hemisphere ice sheets (Haug et al., 2005; Haug and Tiedemann, 1998). However, more heat was also brought to high latitudes associated with an intensified Gulf Stream, preventing ice sheet growth. Thus, astronomical triggering has been proposed as a cooling mechanism (Haug et al., 1999), despite that model simulation suggests additional cooling mechanisms needed to produce the intensive NHG (Lunt et al., 2008b). Recently, we revised this model and

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http://dx.doi.org/10.1016/j.palaeo.2017.07.022
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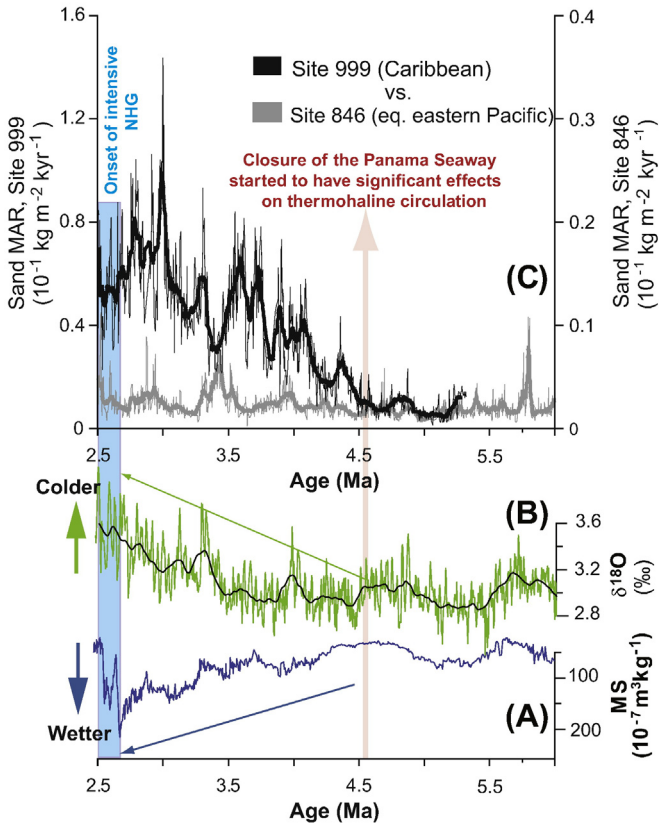

Fig. 1. Comparison of the loess magnetic monsoon proxy record from Chaona, central Chinese Loess Plateau (Song et al., 2001) (A), the benthic oxygen isotope record (Shackleton et al., 1995) (B) from ODP Site 846, Eastern Equatorial Pacific Ocean, and the carbonate sand-fraction mass accumulation rates (MAR) (Haug and Tiedemann, 1998) (C) from ODP Site 999, Caribbean Sea, and Site 846, eastern equatorial Pacific Ocean. The black curve in (B) is a 30-point running average of the gray curve. The Pearson correlation coefficient between (A) and the black curve in (B) during the intervals 6-4.6 Ma and 4.6-2.7 Ma is equal to −0.83 and 0.82, respectively. NHG: Northern Hemisphere glaciation. MS: magnetic susceptibility.

emphasized role of closure on the Pacific Ocean instead of the Atlantic Ocean (Nie et al., 2014). Haug and Tiedemann (1998) presented carbonate sand fraction mass accumulation rate records from the East Equatorial Pacific Ocean and the Caribbean Sea and found they diverge after ~4.5 Ma (Fig. 1). They argue that this divergence was due to the formation of the less corrosive North Atlantic Deep water, which replaced the more corrosive Antarctic Intermediate Water in the deep Caribbean Sea. They argue that the increased formation of the North Atlantic Deep water was a result of gradual closure of the Panama Seaway, which reached a critical sill depth at 4.5 Ma and intensified the Gulf Stream. An intensified Gulf Stream would transport more warm and saline water to the North Atlantic Ocean, promoting evaporation and North Atlantic deep water formation. In addition, Haug et al. (2003) calculated planktonic foram $\delta^{18}O$ difference between the East Equatorial Pacific Ocean and the Caribbean Sea and found the difference was negligible before ~4.5 Ma but increased dramatically since then. They argue that gradual closure of the Panama Seaway since the mid-Miocene reached a critical sill depth (~100 m) that significantly restricted surface water exchange between the tropical Pacific Ocean and the Caribbean Sea at 4.5 Ma. Because the NE trade winds constantly brought moisture from the Caribbean Sea and the tropical Atlantic Ocean to the tropical Pacific Ocean, this caused freshening of the Pacific Ocean (Haug et al., 2003). Critically, we proposed that freshening of the Pacific Ocean triggered a sea-air positive feedback, which not only cooled climate, but also intensified the East Asian summer monsoon and meridional moisture transport (Nie et al., 2014) (Fig. 1).

If this model is correct, it is likely that ice volume and East Asian summer monsoon system will have a clipped response to insolation forcing starting from ~4.5 Ma. We argue that this is most easily told from the 405-kyr cycles. This is because relationships between insolation forcing and the 41-kyr and 23-kyr cycles are likely highly non-linear (Huybers, 2006; Lisiecki and Raymo, 2007; Liu et al., 2008; Raymo et al., 2006; Raymo and Nisancioglu, 2003) and relationship between the 100-kyr cycles and insolation forcing before the Quaternary is complicated (Lisiecki, 2010; Nie et al., 2008b; Nie, 2011; Rial et al., 2013). If the NH ice volume and the East Asian summer monsoon did have a clipped response to insolation forcing at ~4.5 Ma associated with gradual closure of the Panama Seaway, the 405-kyr cycles in paleoclimatic records would have increased amplitude and close phasing to the 405-kyr eccentricity signal.

2. Pliocene intensification of the 405-kyr cycles and NHG

The 405-kyr cycles were filtered in Analyseries with a bandwidth of 333–500 kyr (Paillard et al., 1996). The targets include an East Asian summer monsoon record based on stacking of magnetic susceptibility and carbonate content on the Chinese Loess Plateau (Sun et al., 2010), and the benthic oxygen isotope record stack (Lisiecki and Raymo, 2005) (Fig. 2). The eccentricity's 405-kyr cycles were also extracted for comparison (Laskar et al., 1993). Phase difference was calculated based on peak age difference between each filtered record (Fig. 2). This is a better way than evolutive spectral method in determining the phasing difference when the concerned climatic periodicity is long and the time series is only several times longer than the concerned climate cycle.

It is clear from the phasing relationship (bottom panel of Fig. 2) that both summer monsoon and ice volume had decreased phase difference from the eccentricity forcing at 4.5 Ma. Accordingly, the amplitude of the 405-kyr cycles in both the summer monsoon and the ice volume records amplified after ~4.5 Ma. Filtered signal is sinusoid-shape and, thus, might distort phase difference of the original records. This is particularly true for the sawtooth waveform during the past 1 Ma (Lisiecki, 2013), where this method resulted in increased phase lag between insolation and benthic oxygen isotope record (Fig. 2E), whereas cross-wavelet analysis and direct comparison clearly suggested that the benthic oxygen isotope and eccentricity were phase-locked after 1 Ma (Lisiecki, 2010). In addition, the slight lag of ice volume and monsoon relative to eccentricity between 4.5 and 1 Ma might also come from distorted nature of filtering. Despite these limitations, useful information can still be obtained by focusing on the general pattern of filtered records younger than 1 Ma (Fig. 2).

Previously, we did not consider the phasing relationship and attribute the intensification of the 405-kyr cycles at ~4 Ma to climate system's clipped response to insolation associated with Pliocene uplift of the Tibetan Plateau (Nie et al., 2008c). However, here we found that the phasing difference between eccentricity and monsoon or ice volume decreased clearly as early as 4.5 Ma and both the ice volume and the monsoon records have initiated a trend at the same time (Figs. 1 and 2). Because there is no strong evidence supporting a phase of uplift of the Tibetan Plateau around 4.5 Ma, we revise previous forcing mechanism hypothesis for Pliocene intensification of the 405-kyr cycles in paleoclimatic records and argue that closure of the Panama Seaway was the ultimate forcing for this climatic event. Planktonic oxygen isotope difference between the Caribbean Sea and the east Equatorial Pacific Ocean increased from close to zero to 1‰ at ~4.5 Ma, which was attributed by Haug et al. (2003) to shoaling of the Central American Seaway and freshening of the tropical Pacific Ocean. The fresher tropical Pacific Ocean at 4.5 Ma can be transported to North Pacific via ocean currents, which would decrease freezing point for cold seawater in North Pacific. This would potentially cause more sea ice formation and climate cooling in the North Pacific area, intensifying the North Pacific high pressure system (Motoi and Chan, 2010; Nie et al., 2014). Critically, this would

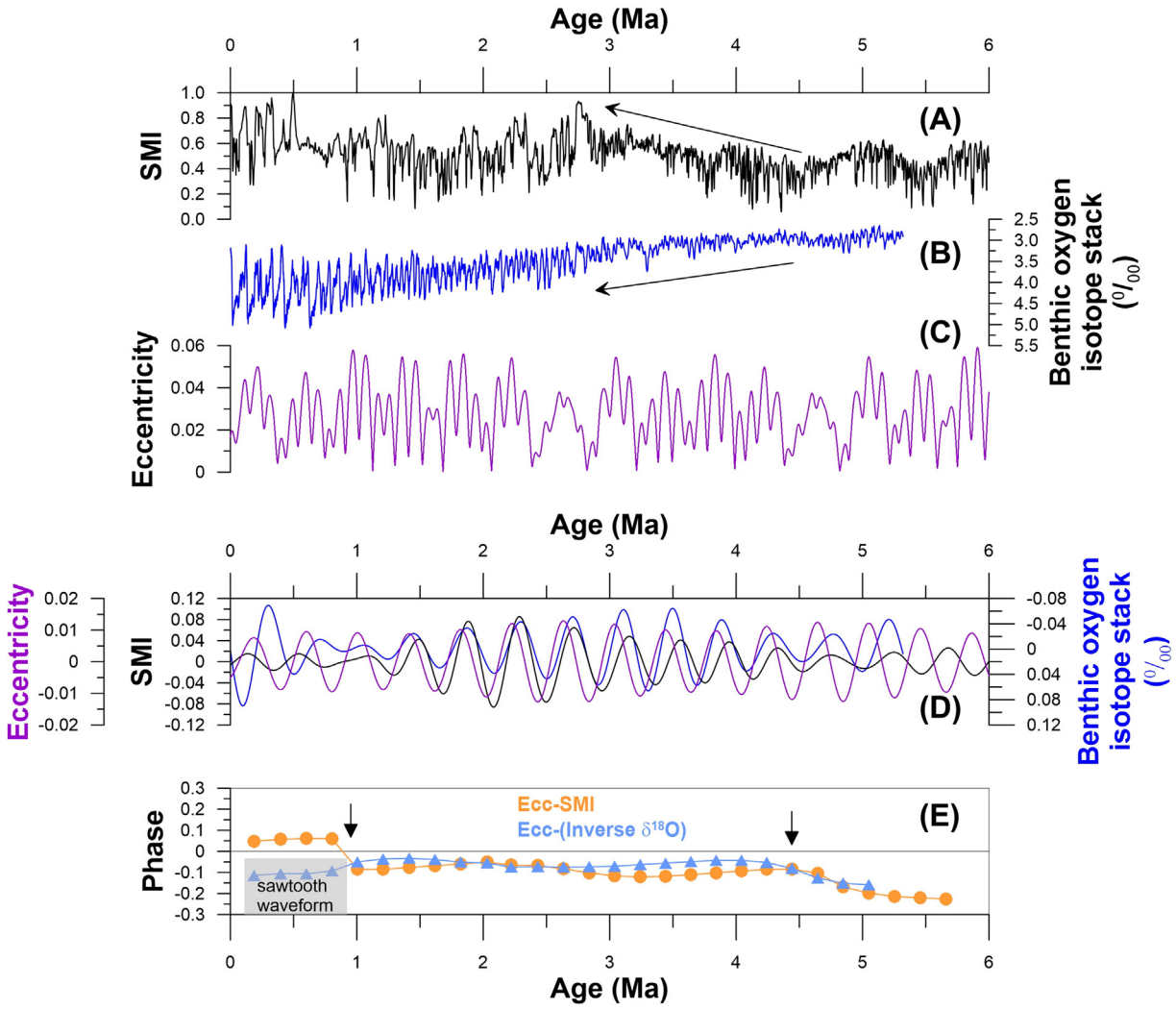

Fig. 2. Comparison of the summer monsoon index (SMI) record (A) (Sun et al., 2010), the benthic oxygen isotope record (B) (Lisiecki and Raymo, 2005), eccentricity data (C) (Laskar et al., 1993) and their 100-kyr component (D) during the past 6 Myr. (E) shows the phasing relationship between eccentricity and the SMI and between eccentricity and the inverse benthic oxygen isotope stack.

cause southerly and southeasterly anomaly and intensify the East Asian summer monsoon (Motoi and Chan, 2010; Nie et al., 2014). Intensified East Asian summer monsoon would be able to transport more fresh moisture to north Pacific and further intensify the North Pacific high pressure system (Emile-Geay et al., 2003; Motoi and Chan, 2010; Nie et al., 2014). Thus, a sea-land positive feedback took place, which was responsible for monotonic trends in paleoclimate records from 4.5 to 2.7 Ma (Nie et al., 2014). This feedback mechanism caused simultaneous climate cooling and East Asian summer monsoon intensification and made the two different climate components have clipped response to insolation forcing and, thus, intensified their sensitivity to eccentricity forcing. In summary, the 405-kyr cycles support that the Pacific sea-atmosphere positive feedback mechanism triggered by gradual closure of the Panama Seaway is an important forcing for the intensive NHG. We note that this conclusion does not exclude atmospheric CO_2 concentration decrease as additional cooling force for the NHG.

Although there is no doubt that formation of the Panama isthmus was a long geological process, the timing for final-stage closure of the Panama Seaway, which is critical to determine surface ocean heat and salinity conditions, is a debating issue. Originally, the closure was assigned to between 6 and 3 Ma based on comparison of tropical Pacific and Atlantic/Caribbean benthic carbon and planktonic oxygen isotope records (Keigwin, 1982). Later high-resolution studies refined this work and suggested that shoaling of the isthmus to 100 m occurred at ~4.5 Ma (Haug and Tiedemann, 1998; Haug et al., 2003) and closure was adequately complete to allow widespread land mammal exchange by 2.7 Ma (Webb, 1997) despite the possibility that land mammal exchange might reflect climate forcing and not be direct evidence for final closure (Molnar, 2008). In contrast, provenance studies in the Pacific and the Atlantic Ocean revealed that an early closure timing (5 Ma) (Frank et al., 1999) and Panama tectonic studies suggested a connection between the Americas may have been in place for 10 Myr or longer (Montes et al., 2012). Despite it looks like that these debates might weaken the robustness of our model, the key to our model is formation age of the salinity difference between the Pacific and the Caribbean Sea/Atlantic Ocean, which was clearly recorded to occur at ~4.5 Ma (Haug et al., 2003).

It is also noteworthy that the 405-kyr cycles are pretty pronounced in benthic carbon isotope records beyond the studied interval (Paillard and Donnadieu, 2014; Pälike et al., 2006; Tian et al., 2014; Wang et al., 2004, 2010). Indeed, the power of the 405-kyr cycles in the benthic carbon isotope records decreased from 10 to 5 Ma and the power did not increase after 4.5 Ma as for the monsoon and ice volume records (Paillard and Donnadieu, 2014). We note that this observation is, however, consistent with our model. Because the benthic carbon isotope records did not show either an increasing or a decreasing trend from ~4.5 Ma (Paillard and Donnadieu, 2014; Wang et al., 2010), our model (clipped response to insolation forcing) predicts that the 405-

kyr cycles should not show increased amplitude for the carbon system. Both the data trend and the 405-kyr cycle amplitude at 4.5 Ma demonstrate that carbon system was decoupled from the ice volume and monsoon systems. Obviously, the salinity difference establishment between the Pacific and the Atlantic Ocean affected the monsoon and the ice volume but not the carbon cycle.

3. Implications for the MPT

The mid-Pleistocene transition (MPT) at ~1 Ma (climatic periodicity transition from 41-kyr to 100-kyr dominance) (Clark et al., 2006; Clark and Pollard, 1998; DeBlonde and Peltier, 1993; Imbrie et al., 1993; Liu et al., 2008; Mudelsee and Schulz, 1997; Paillard and Parrenin, 2004; Rutherford and D'Hondt, 2000) is another perplexing question in paleoclimate research. As for forcing mechanisms for intensified 100-kyr cycles after the MPT, numerous models have been proposed. Imbrie et al. (1993) did an excellent review on potential forcing mechanisms for dominant 100-kyr cycles in paleoclimatic records during the Late Quaternary and work in the past two decades is still within this framework. The intensified 100-kyr cycles have been generally attributed to two potential factors: ice sheet dynamics (Abe-Ouchi et al., 2013; Oerlemans, 1980) and internal oscillation associated with tropical process or carbon cycle (Nie et al., 2008b; Rutherford and D'Hondt, 2000; Saltzman and Maasch, 1988). For example, one group of models proposed the intensified 100-kyr cycles came from bundling of 4–5 precessional cycles and/or 3–4 obliquity cycles (Huybers, 2011; Liu et al., 2008) and ice sheets reached a critical size after 1 Ma so that they would not react with insolation forcing linearly. The other group of models proposed that the intensified 100-kyr cycles came from interaction between ice sheets and bedrock (Abe-Ouchi et al., 2013; Pollard, 1982). In contrast, models arguing for internal oscillation proposed that the 100-kyr cycles came from carbon cycle or processes in tropics and the 100-kyr cycles in carbon cycle or tropic processes intensified after ~1.5-1.0 Ma, causing intensified 100-kyr cycles in paleoclimatic records (Maasch and Saltzman, 1990; Nie et al., 2008b; Rial et al., 2013; Rutherford and D'Hondt, 2000; Saltzman and Maasch, 1988; Short et al., 1991). Again, here considering the 405-kyr cycle variability will be able to cast new light on forcing mechanisms for intensified 100-kyr cycles in paleoclimatic records after ~1.0 Ma.

We have not been able to propose a reasonable mechanism for decreased power in the 405-kyr band monsoon and ice volume record after 1 Ma. However, Rial et al. (2013) proposed that, after 1 Ma, the 405-kyr cycles could have frequency modulated 100-kyr cycles and caused the intensification of the 100-kyr cycles and decreased power in the 405-kyr band. It seems that this is the only available model that can explain both decreased power of the 405-kyr band and increased power in the 100-kyr band in the ice volume records. We note that this hypothesis does not exclude channeling of precessional or obliquity cycles into ~100-kyr cycles as additional forcing for the 100-kyr cycles in the late Pleistocene. However, considering the 405-kyr variability emphasizes that intensification of the 100-kyr cycles during the late Pleistocene should be related to energy transfer from the 405-kyr band as well and this factor has not been emphasized before (Rial et al., 2013). Although model studies showed that either ice sheet dynamics (Abe-Ouchi et al., 2013) or internal oscillation associated with tropical processes or carbon cycle alone (Rial et al., 2013) was able to explain the intensification of the 100-kyr cycles, perhaps, the ultimate forcing for intensification of the 100-kyr cycles during the late Pleistocene was related to both ice sheet dynamics and internal oscillation. After all, power of the Plio-Pleistocene 100-kyr paleoclimatic records showed an inverse relationship with that of the 100-kyr eccentricity data (Lisiecki, 2010; Nie, 2011), supporting that the climate system has internal oscillations with a periodicity of ~100 kyr (Rutherford and D'Hondt, 2000).

Despite Rial et al. (2013) proposed a mathematical model to account for decreased power of the 405-kyr band in paleoclimatic records, their model did not explain why this decrease occurred between 1.5 and 1 Ma. Many climatic events occurred between 1.5 and 1 Ma. For example, the Indian monsoon records exhibit major phase changes relative to precession and obliquity (Clemens et al., 1996) and African climate became more arid (deMenocal, 2004). Loess deposition rates on the Chinese Loess Plateau increased (Bloemendal et al., 1995) and loess magnetic susceptibility began to have a good correlation only with the interglacial ice volume changes (Nie et al., 2008a), a result typical seen when climate system crosses a climatic threshold (Ruddiman, 2000). In addition, tropical Atlantic data recorded the first significant weakening of the North Atlantic deep water formation (Raymo et al., 1990) and the tropical semiprecession cycles started to propagate to higher latitudes (Rutherford and D'Hondt, 2000), accompanied with increased 100-kyr power in ice volume and tropical sea surface temperature records (Liu et al., 2008). Furthermore, Wang et al. (2010) noticed that although the 405-kyr cycle power decreased after 1.5 Ma for open ocean sites, the power did not decrease for the isolated Mediterranean Sea site. Also, a clear anti-phase relationship was established between the 100-kyr-band oxygen and carbon isotope records from 1.5 Ma in open ocean sites. Therefore, they attributed the damped 405-kyr signal after 1.5 Ma to a major change in the oceanic carbon reservoir and these observations suggest a low-latitude origin of the 405-kyr cycles, likely tied to monsoon-caused weathering (Li and Wang, 2015). Obviously, this topic needs further research.

4. Conclusions

We observed that the 405-kyr cycles in proxy records for the East Asian summer monsoon and global ice volume intensified and became phase-locked to eccentricity forcing at ~4.5 Ma. Based on this observation, we revised previous forcing mechanism hypothesis for Pliocene intensification of the 405-kyr cycles in paleoclimatic records and proposed that the establishment of salinity difference between the Pacific Ocean and the Caribbean Sea at ~4.5 Ma was the ultimate forcing for this climatic event. Previous studies proposed that an ocean-air positive feedback mechanism was initiated in the Pacific Ocean at ~4.5 Ma associated with the establishment of salinity difference between the Pacific Ocean and the Caribbean Sea. We argue that this feedback mechanism caused simultaneous climate cooling and East Asian summer monsoon intensification and made the two different climate components have a clipped response to insolation forcing and, thus, intensified sensitivity to eccentricity variations.

Acknowledgments

We thank C. Huang and another reviewer for the comments, and thank Guest Editor H. Hong and Editor-in-Chief T. Algeo for editing and handling our paper. We also thank L. Gong for helping with figure preparation. This work was funded by the National Key Research and Development Program of China (Grant No. 2016YFE0109500), the (973) National Basic Research Program of China (Grant No. 2013CB956400), and the National Natural Science Foundation of China (Grant Nos. 41422204; 41372036; 41172329; 41290253).

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